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I. The BATSE/GRO Experiment

W. Paciesas continued to support BATSE in meetings and reviews related to testing, calibration, and data analysis software development. He is the BATSE representative on the GRO Data Operations Group (GRODOG) and the GRO Users' Committee. The main GRODOG effort thus far has been to produce a report describing the present status and future plans of the GRO data analysis effort. Having been a leader in this effort, Paciesas provided a description of the BATSE planning for the report, which is currently being prepared for submittal to the GRO Users' Committee in October. Portions of this material was used as the basis for an invited paper presented by Paciesas at the GRO Workshop in April which was also included in the Workshop proceedings (Paciesas et al., Appendix A).

Paciesas served as scientific liaison overseeing development of the BATSE Spectral Analysis Software (BSAS) by GSFC. The development effort passed a major milestone, having completed a successful Critical Design Review on January 19-20, 1989. Paciesas and G. Pendleton served on the review team. The scheme for storage of detector response matrices received considerable attention at this time.

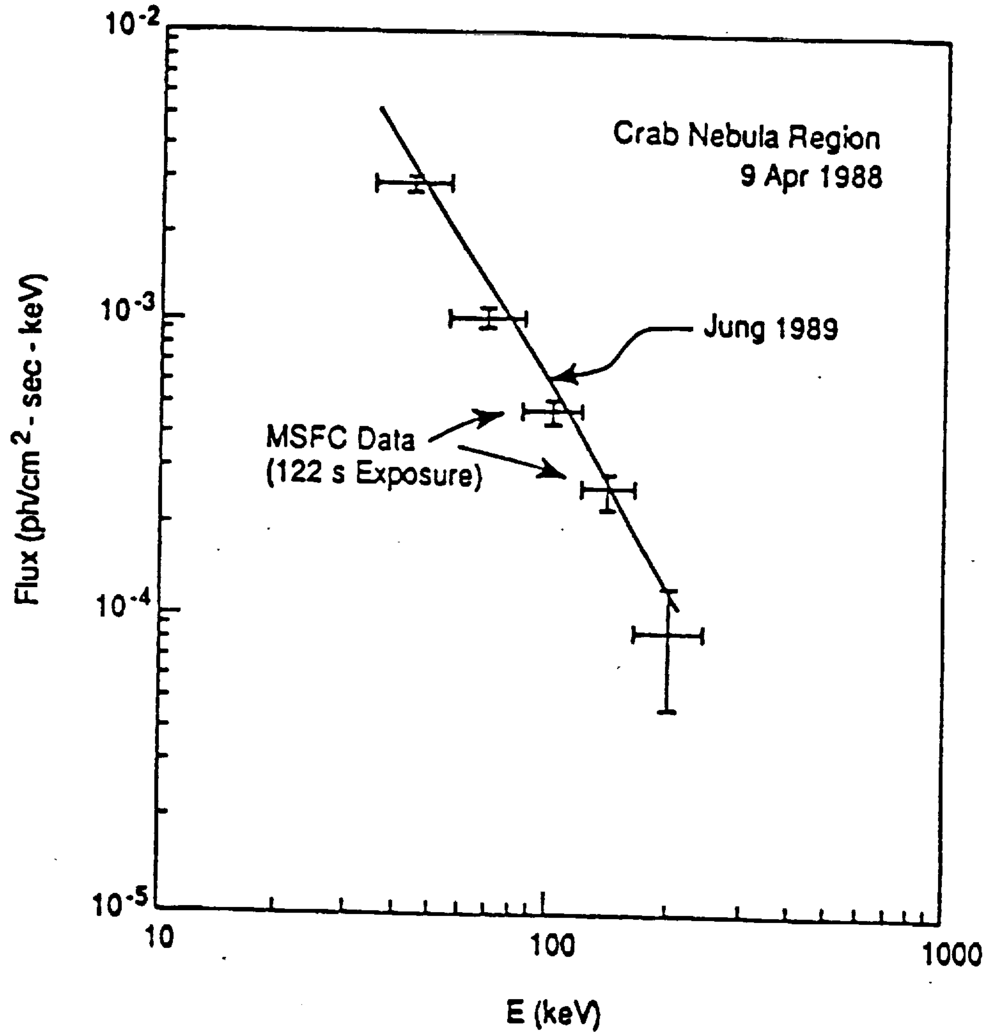
Pendleton has led the joint UAH/MSFC effort to develop matrices suitable for use with the BSAS spectral deconvolution algorithms. He participated in the radiation source survey at TRW in March which provided calibration data for comparison with simulations. He is serving as BATSE representative on the GRO Mass Model Committee which held its first meeting in February. His simulation software uses the EGS electron-photon shower code along with a custom general geometry routine. The initial efforts to simulate calibration data have been very successful and Pendleton presented a poster paper at the GRO Workshop in April describing these developments (Pendleton et al., 1989, Appendix B).

II. Balloon-Borne Observations of Supernova 1987A

Paciesas and Pendleton have both been active in the data analysis effort for supernova balloon flights of October 1987, April 1988, and November 1988. Paciesas performed much of the preliminary analysis for the October 1987 and April 1988 flights and wrote major portions of the published paper describing these results (Fishman et al., Appendix C). He also played a major part in field operations for the November 1988 flight, traveling to Alice Springs, Australia, in October/November, 1988, to support this successful flight.

Using the same software package as developed for BATSE, Pendleton has produced detector response matrices for the balloon flight detectors and has used these to produce deconvolved spectra of SN 1987A for the first two balloon flights. He presented a poster paper at the January 1989 AAS meeting in Boston describing his use of B. Schaefer's model-independent spectral deconvolution technique in this context. G. Fishman presented a paper on SN 1987A at the same meeting using Pendleton's results derived with both model-dependent and model-independent techniques. Copies of the abstracts are included in Appendix D.

As a check on the validity of the spectral deconvolution, Pendleton and K. Hong produced spectra of the Crab Nebula from the short observation of that source during the April 1988 flight. The Crab spectrum was reproduced satisfactorily, as shown in Figure 1. This successful use of the model-independent spectral deconvolution technique also serves as an important validation of the BSAS algorithms.



Hard X-ray spectrum of the Crab Nebula obtained with a 112 s observation on the balloon flight of April 9.1988. The data have been deconvolved using a model-independent inversion algorithm. Shown for comparison is the spectrum obtained by Jung (1989).

Figure 1

Appendix A

(Published in the Proceedings of the GRO Science Workshop)

The BATSE Data Analysis System and Implementation of the Guest Investigator Program

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ABSTRACT

The Burst and Transient Source Experiment (BATSE) detects sources by looking for time variability, either intrinsic to a source (such as γ-ray bursts or pulsars) or induced by earth occultation. Techniques for analysis of the data are dependent on the nature of the variability; moreover, the BATSE data are formatted differently for the different analysis techniques. Certain software functions (such as spectral deconvolution) are useful for all sources once the data have been processed sufficiently. We describe herein a set of software packages which will be used to analyze the BATSE data. We also summarize the nature of the data bases which are produced during the analysis and discuss their potential availability for guest investigations.

The primary facility for analysis of BATSE data will be located at NASA/Marshall Space Flight Center (MSFC). Additional facilities at NASA/Goddard Space Flight Center (GSFC) and the University of California, San Diego (UCSD), will be capable of implementing a subset of the functions of the primary facility. Guest Investigator support will be available at the primary analysis facility during the GRO mission.

1. Description of Data Analysis Flow

BATSE data is transmitted daily from the Packet Processing Facility (PACOR) at GSFC to MSFC via the GRO Data Distribution and Command System (DDCS) in increments of one day. Figure 1 illustrates the flow of data after receipt at MSFC. Storage of the raw data in the BATSE data archive is a mission operations (MOPS) function. The MOPS functions which relate to data analysis also include first-cut monitoring of data quality, monitoring of detector gain and resolution, calculation of various secondary spacecraft parameters such as the local magnetic field, and quick-look science analysis such as first-cut burst location. The MOPS functions also include distribution of a portion of the raw data to co-investigators at GSFC and UCSD.

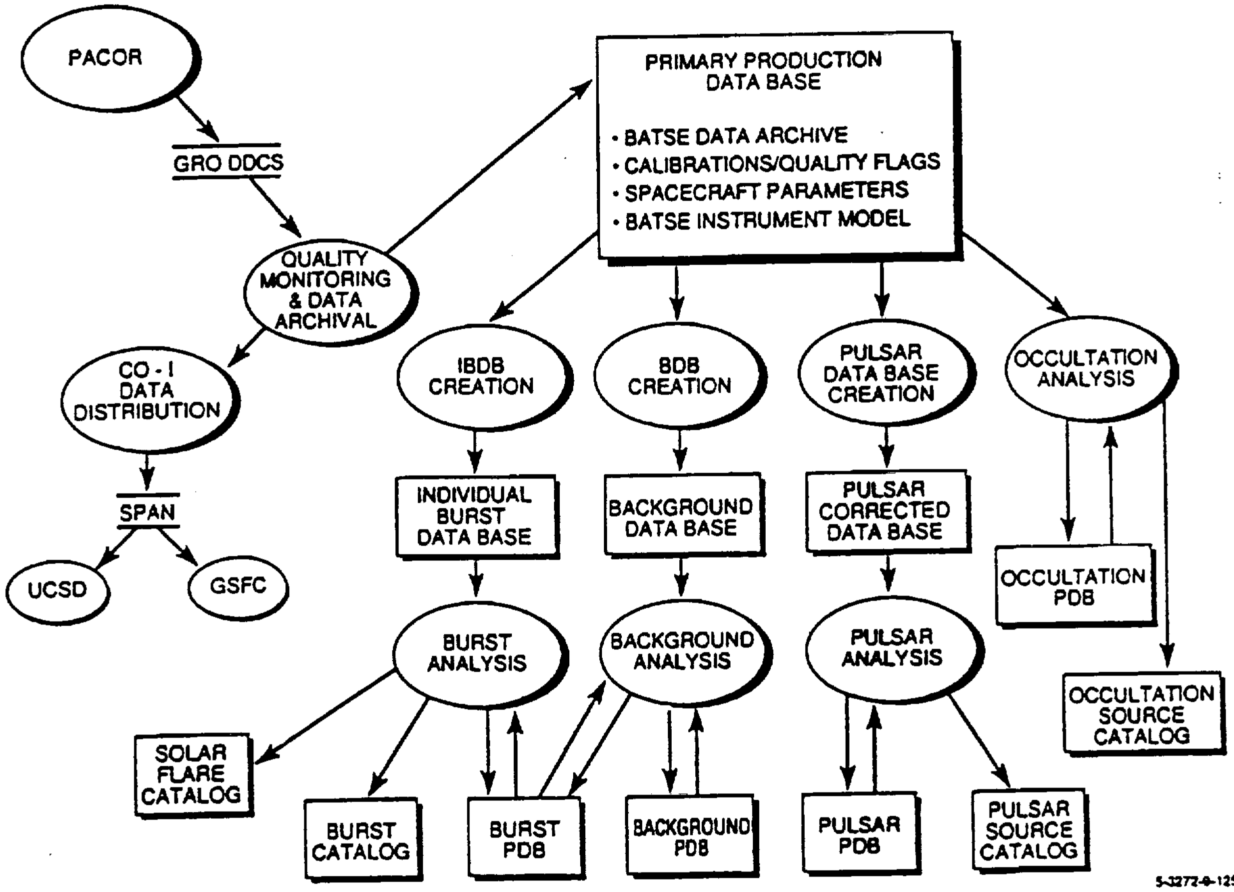

Figure 1: BATSE Data Analysis Flow Diagram

The BATSE data archive is stored on the Marshall Archival System (MARS), an optical disk storage system which is maintained by MSFC for archival of flight data from various experiments. The other components of the primary data base are stored initially on magnetic disk, with archival backups to either local optical disk or magnetic tape. Analysis using a particular technique generally will proceed by generation of the appropriate secondary data base from the primary data base using the raw data combined with the calibration data, quality criteria, spacecraft parameters, and the BATSE instrument model. (The occultation analysis is expected to be an exceptional case, as discussed below.) Subsequent analysis results and processed data are stored in tertiary Processed Data Bases (PDB's) which are managed using the commercially-available INGRES data base management system.

Burst analysis is the primary BATSE science objective. The Individual Burst Data Base (IBDB) which is produced for burst (and solar flare) analysis contains essentially the raw data dump of the on-board burst memory together with associated background data. Burst analysis software performs gain correction, constructs spectra and time histories with optional rebinning and background subtraction, and stores the accumulated data in the Burst PDB. Burst analysis functions include burst location, temporal analyses (Fourier power spectra, epoch folding, etc.), time-resolved spectral deconvolution, display of temporal evolution of spectral-fit parameters, and derivation of parameters for global studies such as $\log N/\log S$. Intermediate and final results may be stored in the Burst PDB. Burst and solar flare catalogs are maintained and will be made available for public access.

Pulsar analysis is a secondary BATSE science objective. Production of the Pulsar Corrected Data Base (PCDB) takes one of two forms depending on whether on-board folding has been performed or not. If folded on-board, various corrections for folding-period offset, overflows and unequal bin widths must be applied in addition to the standard Doppler corrections. If on-ground folding is to be performed, the PCDB consists mostly of raw rates, possibly binned in time and/or energy, with appropriate Doppler corrections. Pulsar analysis includes functions for light curve display, light curve model fitting, time-resolved spectroscopy, and display of temporal evolution of fit parameters. Intermediate and final analysis results may be stored in the Pulsar PDB. A pulsar source catalog is maintained and will be made available for public access.

The Background Data Base (BDB) is intended to facilitate studies of background variations which may lead to development of improved background models and/or discovery of non-triggered bursts or intermediate-timescale transient events. Software analysis tools consist primarily of display programs, spectral analysis functions such as line-fitting, and temporal search algorithms. Intermediate and final results may be stored in the Background PBD. Application software may be developed by users as required for particular investigations.

The monitoring of persistent and long-term transient sources using earth occultation is also a secondary BATSE objective. This analysis is expected to be particularly complex, requiring careful scientific monitoring. The software is expected to evolve considerably as the mission proceeds; hence, data base definition is still in progress. Present planning indicates that creation of a secondary data base as in the other types of analysis is probably not useful. The major occultation analysis software would work directly on the raw data, developing source time histories with modest spectral resolution which would be stored in the Occultation PDB. Spectral deconvolution of the data may be performed and the results also stored in the PDB.

A primary component of all data analysis is spectral analysis, including line searches and spectral deconvolution. A software package, the BATSE Spectral Analysis Software (BSAS) is being developed for this purpose by BATSE co-investigators at GSFC and it will be transported to other BATSE team facilities at MSFC and UCSD. Though primarily intended for analysis of burst spectra, the package will also be used for any spectral studies in the other analysis modes.

2. Instrument Analysis Center Data Bases

Three types of secondary data bases are produced for data analysis: the Individual Burst Data Base (IBDB), the Background Data Base (BDB), and the Pulsar Corrected Data Base (PCDB). At MSFC, these are created as needed for a specific application from the Primary Production Data Base and generally not archived. The IBDB and BDB formats are used to distribute a subset of the BATSE data to co-investigators at GSFC and UCSD, where local archives of these data bases are maintained. These data bases generally consist of essentially raw data which satisfies certain quality criteria, together with associated calibration parameters, spacecraft parameters, and pointers to relevant instrument model data (primarily response matrices). Pulsar data undergo some corrections to eliminate certain types of overflow conditions. The data may be summed over selected time and/or energy domains. Occultation analysis does not lend itself to useful compression at this level, and we do not anticipate creating a secondary data base for this purpose.

The tertiary PDB's contain gain-corrected spectral files and time-history files, together with various other files of intermediate or final analysis results. There are four PDB's: one each for burst, background, pulsar, and occultation analyses (solar flares are maintained in the burst PDB).

The spectral and time-history files are typically binned in the energy and/or time domains relative to the secondary data base. Header relations and pointers to each of these files are maintained and managed with INGRES. INGRES also effectively maintains a history of analyses performed for each source. Individual users will typically have their own copy of a subset of the PDB while a particular investigation is in progress. Selected results and intermediate data files may then incorporated into the institutional master copy of a PDB at the user's option (appropriate privileges are required). Inspection of the institutional PDB thus enables a quick survey of work already completed on a particular source and helps to eliminate duplication of effort.

3. Public Data Bases & Data Products

Within the GRO Guest Investigator (GI) program (Bunner 1989) a significant distinction is made between high-level and low-level data. The high-level data products will be analyzable in a relatively independent manner whereas use of low-level data will require close collaboration with the Principal Investigator (PI) team, typically involving a period of residence at a PI institution.

Any data which can be stored in a BATSE PDB are, in principle, available as high-level data. Standard sets of time-histories and pulse-height spectra (with associated response matrices and calibration parameters) will be produced for each burst, solar flare, pulsar (on-board folding only), and bright occultation source. Requests for non-standard data sets (*e.g.*, different energy or time binning, different burst data types, weaker occultation sources, raw data for on-ground pulsar folding or other temporal analysis) will be considered special processing, and will be honored on a resource-limited basis. High-level data will be available either in Flexible Image Transport System (FITS) format or in the BATSE PDB format. The latter will be useful if the BSAS package is transported to a GI system.

The remaining BATSE data (secondary data bases or, in the case of occultation analysis, the primary data base) are available to GI's as low-level data. Typically, use of these data products would involve spending some time at MSFC, since no resources have been allocated for GI visits to GSFC or UCSD. Once the GI attains sufficient familiarity with the instrument characteristics and analysis techniques, arrangements to transport relevant software and/or low-level data to another institution will be considered on a case-by-case basis.

Catalogs of BATSE observations/investigations of bursts, solar flares, occultation sources, and pulsar sources will be generated during data analysis. Data analysis catalogs of bursts, solar flares, occultation sources, and pulsar sources will be available for public inspection via remote logon over the Space Physics Analysis Network (SPAN). Access via other means is being considered.

The BATSE burst and solar flare trigger signals are sent in real time to the other instruments on the GRO. As part of MOPS, BATSE will provide additional information such as first-cut location of bursts to interested GRO instrumenters via the GRO DDCS. A similar service will be available via SPAN using VAX mail. Some form of public access via SPAN will be available; the details have not yet been defined.

4. Data Analysis Environment

The BATSE data analysis environment at MSFC consists entirely of Digital Equipment Corporation (DEC) VAX systems in an ethernet cluster physically located in the Space Science Laboratory (SSL; building 4481). Machines on the cluster which are available for BATSE data analysis include a VAX 11/780 and a VAX 8250. Aproximately 600 Mbyte of magnetic disk storage is available for exclusive BATSE use. Hardware which is planned for purchase in FY89 includes three VAXstation 3100's with a total of ~500 megabytes of additional disk storage. Four additional VAXstation 3100's plus an additional 600 Mbyte disk drive for the SSL cluster are planned for purchase in FY90. All systems operate under VAX/VMS. Peripherals available on the cluster include line printers, laser printers, 6250 bpi magnetic tape drives, pen plotters, and an optical disk Write-Once/Read-Many (WORM) drive.

The MARS is used for archival of the raw BATSE data. It is a custom-built optical disk WORM storage system which is shared with other MSFC projects. The system consists of 128 disks in a jukebox arrangement. Each disk has a capacity of ~10 Gbyte, resulting in a total system capacity of ~1 Tbyte. One year of BATSE packet data takes ~1% of MARS capacity. The front-end interface to MARS is a VAX system, running VAX/VMS. ORACLE is used to maintain on VAX disk a catalog of the data archive. MARS is located in building 4487 at MSFC; access to MARS is via an Institutional Area Network.

5. Data Analysis Software

We have somewhat arbitrarily specified the BATSE data analysis software in terms of a number of packages. The current development status of the packages varies. Some are almost completely coded, while others are in requirements specification or preliminary design. We discuss each package in the subsections which follow. First, however, some general comments which relate to software portability are warranted.

- *All BATSE data analysis software runs under VMS.* Use of VMS system-specific calls has been minimized but not prohibited in software development. For software not yet developed, we are considering eliminating such usage. Several packages use proprietary commercial or public domain products which are available in versions which run under other operating systems. We have no plans to perform any tests which would assure that any of our packages which use such software will in fact run under another operating system.

- *Most of the software is written in FORTRAN.* VAX FORTRAN is a superset of ANSI FORTRAN-77. Although all packages are compiled under VAX FORTRAN, some development restrictions exist with regard to use of non-ANSI constructs. Additional restrictions are being considered which may be applicable to future software development.

- For many packages the user shell is a package called Transportable Applications Executive (TAE) which is available from COSMIC (NASA's Computer Software Management and Information Center). Versions of TAE are available for several different operating systems (including UNIX). The PDB's are managed using INGRES, a commercial product which is also available in versions for other operating systems. At least two graphics packages are used: GKS-compatible NCAR Graphics and MONGO.

- The commercial package IDL (or its more recent successor PV~WAVE) may be used in implementing some functions in packages which have not yet entered the coding phase.

5.1. BATSE Spectral Analysis Software (BSAS)

This package is used in all data analysis functions for spectral deconvolution and model-fitting. Routines are available for accumulation and rebinning of spectra from the secondary data bases, background subtraction using several different algorithms, traditional model-dependent least-squares spectral deconvolution, spectral line searches and fitting, model-independent deconvolution using direct matrix inversion, model-fitting to model-independent photon spectral data, display of pulse-height or photon data and model fits, and determination of burst-specific parameters such as fluence. Analysis results are stored automatically in a user version of the PDB and may be stored at the user's option in the appropriate institutional master PDB. The spectral deconvolution is a fairly complex task; however, many astronomers, particularly those with high-energy experience, are familiar with the problems involved.

The package uses TAE, INGRES, and MONGO. In particular, it makes extensive use of INGRES forms for input menus. Graphics hardware which supports Tektronics 4010/4014 standard is required for displays. A certain degree of portability exists because the package is written to be used at three different BATSE institutions: MSFC, GSFC, and UCSD. However, all three have VAX systems running under VMS, and all will have the necessary associated software and graphics hardware.

5.2. Mission Operations

This package is used in performing the daily tasks involved in Mission Operations (MOPS). It includes various routines for communication with the GRO DDCS, monitoring of instrument configuration and performance, mission planning and command generation, instrument model data base management, data archival, and quick-look science. It is also used to distribute data to BATSE co-investigators and GSFC and UCSD via SPAN. It generally operates only on the raw data set from the most recent day. However, files of recent history of selected parameters are maintained; the latter are used as input to certain data analysis functions which maintain a local (non-MARS) archive of certain parameters. Other MOPS functions which relate directly to data analysis include reformatting of data for MARS archival, first-cut data quality monitoring, first-cut burst location, burst time-history display, bright-source occultation monitoring, calculation of secondary spacecraft parameters such as McIlwain (L, B) coordinates, and monitoring of detector gain and resolution. Complexity is moderate in most cases, except for burst location and occultation monitoring, which involve considerable algorithmic subtleties.

The MOPS package uses TAE and GKS-compatible NCAR Graphics. Graphics hardware compatible with 4010/4014 is required for displays. Non-ANSI features of VAX FORTRAN are used extensively. Specific hardware interfaces are required for communication with the GRO DDCS. Although the package was not intended to be used outside MSFC, portions will be adapted for use in data analysis, at which time portability-related improvements may be considered.

5.3. Burst Data Analysis

Some burst data analysis will be accomplished using MOPS software (with minor modifications). BSAS will be used for burst spectral analysis. Additional burst analysis software is required to implement other functions: IBDB generation, optimized burst location, display of sky distributions, sky exposure map computations, isotropy analysis, improved time-history display utilities, burst periodicity studies using epoch-folding or Fourier power spectra, instantaneous burst detection efficiency, etc. This software is still in early development, so portability constraints could be applied if deemed appropriate. Many functions will be implemented using IDL. Some functions are relatively straightforward. Others such as sky exposure map computations are not trivial and require some considerable scientific oversight. Some functions will be require access to the burst PDB and therefore will have an INGRES interface.

5.4. Pulsar analysis

Pulsar analysis software is required to implement various functions: PCDB generation, epoch-folding, Fourier power spectral analysis, lightcurve display utilities, light-curve fitting, pulsar parameter time-history display, etc. This software is in early development, so that portability constraints could be applied where deemed appropriate. Algorithms for these functions are relatively standard. Many functions will be implemented using IDL. Most functions will require access to the pulsar PDB and therefore will have an INGRES interface. BSAS will be used for spectral analysis.

5.5. Occultation analysis

MOPS software will be adapted to use in data analysis for bright-source occultation studies not already performed in MOPS. BSAS will be used for spectral analysis. Some utiltiies are required: sky distributions, source time-history display, etc. Software for this purpose is in early development, so that portability constraints could be applied as appropriate. Complexity is minimal. Additional software is required in order to implement an optimized source search strategy. The algorithms will require considerable refinement in order to reduce systematic errors. IDL will be used extensively in analyses of the systematics. Portability is not expected to be a consideration, since independent analysis of these data is not likely. Some functions will require access to the occultation PDB and therefore will have an INGRES interface.

5.6. Background analysis

Background analysis software is required to generate the BDB and to implement the non-triggered burst search and line-transient search. BSAS will be used for background spectral analysis. Additional software is in early development. Access to the background PDB and burst PDB via INGRES will be required. Systematic subtleties make the background analysis a complex task which is not expected to be performed independently by GI's.

5.7. High-level data base generation

This is a straightforward set of utilities for generation of high-level data for distribution to GI's. The software will extract the necessary data from the appropriate PDB and convert it to FITS format. The package will be developed during the first year of GRO operation.

5.8. Response matrix generation

Sensitivity attainable with both low-level and high-level data products will improve significantly as the instrument model (detector response matrices and atmospheric and spacecraft scattering corrections) becomes more sophisticated. The improvements will result from better Monte Carlo simulations as well as empirical adjustment using data from sources with known locations and/or spectra (*e.g.*, Crab Nebula, solar flares, orbiting nuclear reactors). Software for Monte Carlo modeling exists at MSFC but neither portability nor user-friendliness were seriously considered during development. By nature, the Monte Carlo studies require intensive scientific involvement. Empirical adjustment studies will be performed using the existing analysis routines, with possible use of IDL. Refinement of the response matrices is a major function of the PI team. Our approach to response matrix generation is described by Pendleton *et al.* (1989).

6. Support for Guest Investigators

The GRO science office is expected to provide one scientist to act as GI liaison on a half-time basis. The BATSE team plans to designate one scientist (half-time), one programmer (full-time) and one data technician (half-time) to provide additional GI support. At least one VAXstation 3100 will be available to GI's on a priority basis. The link to SPAN will enable remote logon and access to catalogs, data bases, and software (with appropriate restrictions). Although portions of the BATSE data and software are available at GSFC and UCSD, there are no plans to provide additional resources at either of these sites to support GI's.

7. Data Access Schedule and Mechanisms

Access to low-level data will be available at MSFC beginning in the first year. We anticipate supporting ~2–4 GI's during the first year. Standard high-level data products will be available from MSFC in a *Rev. 0* release during the second year. We anticipate several revised releases of standard high-level data at intervals of about a year. The standard high-level data products will also be incorporated into NASA's Astrophysics Data System (ADS). We plan to deliver data in FITS format to the appropriate ADS node within one year after receipt of data in usable form.

The BATSE burst catalog, solar flare catalog, occultation source catalog, and pulsar source catalog will be available for public access through MSFC during the second year. It is expected that BATSE catalogs will eventually be incorporated into the ADS Astrophysics Master Directory; the schedule for this has not been defined.

ACKNOWLEDGEMENTS

Development of BATSE mission operations and data analysis software is a major task involving too many people to name individually. We appreciate the efforts of staff members of the Space Science Laboratory of the NASA/Marshall Space Flight Center and the Laboratory for High Energy Astrophysics of the NASA/Goddard Space Flight Center as well as those of contractor personnel. The major contractors include Boeing Computer Support Services, Inc., New Technology, Inc., the University of Alabama in Huntsville, Science Applications Research, Inc., and the University of Maryland.

We are also grateful for expert advice and assistance from Jesse Maury, the GRO Project Software Manager.

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Appendix B

(Published in the Proceedings of the GRO Science Workshop)

The BATSE Detector Response Matrices

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Abstract

The detector response matrices for the BATSE large area detectors and spectroscopy detectors are being generated using EGS Monte Carlo simulations that are verified by comparison with experimental data. The format of this procedure is discussed. Data exhibiting the angular response of the detectors are presented. The format in which the detector response matrices are to be stored for general access is described. Future work for refining the matrices is outlined.

1 Introduction

The detector response matrices for the BATSE detectors are necessary for any spectral analysis and for burst location. These matrices charactrize the detector output for a given energy input. The spectral response functions for the BATSE detectors, particularly the large area detectors, exhibit significant Compton tails at higher photon energies. Therefore precise characterization of the detector response matrices is required for any type of photon spectrum reconstruction. Also a thorough understanding of the angular response of the large area detectors is necessary for reliable burst location. Scattering of photon flux off the atmosphere is addressed elsewhere and is not discussed in this paper.

2 Experimental Verification of Monte Carlo Simulations

A comprehensive set of BATSE detector tests have been performed. Those tests focusing on detector spectral response functions are the Angular Response tests and the Absolute Efficiency tests. In these tests the detectors were exposed to monoenergetic nuclear γ-ray sources and spectra were collected. Although a variety of sources were employed, the detector response functions were measured only at the energies of the γ-rays that the nuclear sources produced.

In order to extend the detector response functions between the energies measured in the tests Monte Carlo simulations are employed. The accuracy of the simulation results is confirmed by comparison with the experimental test results. Also, detailed analysis of the simulation results yields an improved understanding of systematic characteristics of the detectors and of the test environment. The simulations can be used to extend the detector response matrices to energies above 3 MeV where measurements have not been performed.

In order to accurately reproduce the experimental measurements with Monte Carlo calculations the detector geometry and test environment geometry must be simulated in detail. These simulations are performed with the EGS electron-photon shower code (Ford *et al.*) and a general geometry routine written by the principal author. Figure 1 shows an outline of the geometry used for the large area detector simulation. The figure is a nearly edge on view of the detector geometry surrounded by objects present in the test environment. Shown are the anticoincidence assembly, the detector crystal assembly, the light collection cone, and a compressed volume for the detector base.

In figure 2 the detector is shown in the angular response test geometry. Here the detector rests on a raised stand and is exposed to a collimated monoenergetic photon beam. The sources used in the angular response tests were placed in a lead collimator with an opening angle of 11.5°. In these tests the detector module was rotated about a vertical axis to positions spanning 360°. Each position corresponded to a specific angle between the detector normal and the incident photon beam. The detector response for both the large area detectors (LAD's) and the spectroscopy (SD's) detectors was measured at each position. The data obtained characterize the angular response of both the LAD's and SD's.

Figure 3 shows the spectra obtained at various angles for the LAD's and SD's from exposure to a Cs^{137} source (a 662 keV γ-ray source) during the angular response tests. The numbers on the graphs themselves (0 degs , etc.) identify the response functions at specific angles between the detector normal and incident photon beam direction. The angular response of the LAD's is quite strong, as intended, where as the angular response of the spec detectors is not as pronounced.

Figure 4 shows spectra generated using the Monte Carlo simulation for an LAD exposed to a Cs^{137} source at 0° and at 90°. The spectra were obtained by taking the energy deposition spectrum in the LAD crystal and subjecting it to two procedures. First the radial response of the crystal was taken into account; the luminosity response measured by the LAD phototubes to an energy deposition at the edge of the LAD crystal is about 85% of the response measured due to an energy deposition at the center of the crystal. This behavior has been measured experimentally and can be characterized by a radial response function. In order to incorporate this feature of the detector response into the Monte Carlo spectra, each energy deposition was adjusted by the radial response function before being added to the energy deposition spectrum. Secondly a statistical broadening function dependent on energy was applied to the data to produce the spectra shown in figure 4. These procedures will be described in much greater detail in a series of forthcoming papers.

3 Detector Response Matrix Storage Format

The actual detector response matrices will be generated in a comprehensive set of Monte Carlo production runs this summer and fall. The detector response matrix data will be stored in rows where each row corresponds to the detector response at a specific input energy. An example of the shape of such a row is the Cs^{137} spectrum which shows the detector response to 662 keV γ-rays. Each of these rows will consist of a 60 point piecewise linear fit that will extend from the detector threshold to 150% of the photopeak energy. What this means is that the spacing between points in a row will be $E_{in} * 1.5/59$. (E_{in} being the input energy). This format results in a compressed matrix for storage.

This storage format has a number of advantages. Most features of the detector response matrix, are linearly dependent on input energy. Therefore if it is necessary to determine the detector response at an input energy between two of the rows of the response matrix it will be more accurate to extrapolate between two rows in the compressed matrix space. For example in the compressed matrix space the photopeaks of different input energies line up and the extrapolation between the peaks is more accurate. This is the extrapolation technique employed in the creation of rebinned detector response matrices when calculating the values at bin edges between matrix rows. The matrix can then be recast in conventional energy space for use in analysis. The restoration of the matrix to conventional uncompressed form will be an automatic feature of the spectral analysis software (Schaefer *et al.*,1989). The user will select the binning and energy range desired and the software will produce the appropriate matrix in standard uncompressed form. Therefore the compressed matrix storage format will not inconvenience the user.

Another advantage of the compressed format is that it optimizes the ratio of information content to storage space for the matrices. This is true for two reasons. First, the uncompressed matrix has a large number of zero elements at output energies above the input energy. These are not present in the compressed format. Second, since the detail necessary at lower energies is not necessary at higher energies, no information is gained by storing the matrix in uncompressed form.

In the compressed format any number of rows can be stored (i.e. the format is not limited by the constraints of a square matrix). This means that we can store the SD response matrices over the energy range from 15 keV to 100 or more MeV. Storing such a matrix in conventional form with a 2 keV accuracy (necessary at around 15 keV) would require something like a 50,000 $\times$ 50,000 element array which is way too big. The compressed matrix format allows us to store the same data in a 60 $\times$ 100 or 200 element array whose size we can adjust depending on the accuracy desired.

Finally the angular response must be addressed. The matrix format above applies to a detector response matrix calculated for γ-rays at one particular angle of incidence with respect to the detector normal (one particular polar angle). Azimuthal variations in the detector response matrices at fixed polar angles are not considered in the first generation of detector response matrices. However the detector response matrices must span polar incidence angles from 0^o to 90^o or more. To store these matrices efficiently each element of the compressed matrix is parameterized in θ, the polar angle of incidence. At present a 4 coefficient parameterization of each matrix element is calculated. The matrix elements at incidence angle θ are calculated from

$$X = A * F_1(\theta) + B * F_2(\theta) + C * F_3(\theta) + D * F_4(\theta)$$

This parameterization technique was adopted because of the complexity of the angular response of the LAD's. Here each element of the array can vary with θ independently. Therefore it can handle virtually any θ dependent variations in the response matrices. At this time the four functions $F_1(\theta)$ through $F_4(\theta)$ are those of a general cubic polynomial. If during the matrix data generation phase we find another set of four functions that produce a significantly more accurate fit to the angular dependence of the detector response we will use those. The coefficients A, B, C, and D are the quantities that will be stored. This way the entire response matrix set can be stored in four compressed matrices of coefficients. This paramaterization is a structure internal to the spectral analysis software. The software will automatically generate the uncompressed matrix for the appropriate angle of incidence for each detector.

As our understanding of the detector response matrices increases, azimuthal dependence and individual detector characteristics can be incorporated into the response matrix set. This will result in an increase in the number of parameters per matrix element and separation of the eight individual detector response matrix sets. The improvements in detector response will be generated with the GRO mass model code after it is fully tested and compared with experimental tests. The GRO mass model code still under construction will be tested using the data obtained during the GRO source survey test. In this test γ-ray sources were exposed to the entire spacecraft with the BATSE modules attached in flight configuration. Data were collected from the entire BATSE system operating in this case as an all spacecraft monitor. The data will be used to determine the contribution of spacecraft scattering to the response matrices. They will also be used to test the accuracy of the mass model geometry code. The test setup will be simulated in detail and the simulated spectra generated will be compared with the data collected to verify the operation of the code. Once the simulation code is shown to be operating correctly the geometry for the spacecraft in orbit will be input. With this simulation it should be possible to incorporate azimuthal dependence into the detector response matrices.

4 Implementation of the Matrices

The basic response matrices including angular dependence will be implemented in the software before launch. Matrices with azimuthal dependence will be implemented as soon as the simulation code can generate them. The simulation software will be maintained in working order in case more detailed knowledge of some aspect of detector response is desired.

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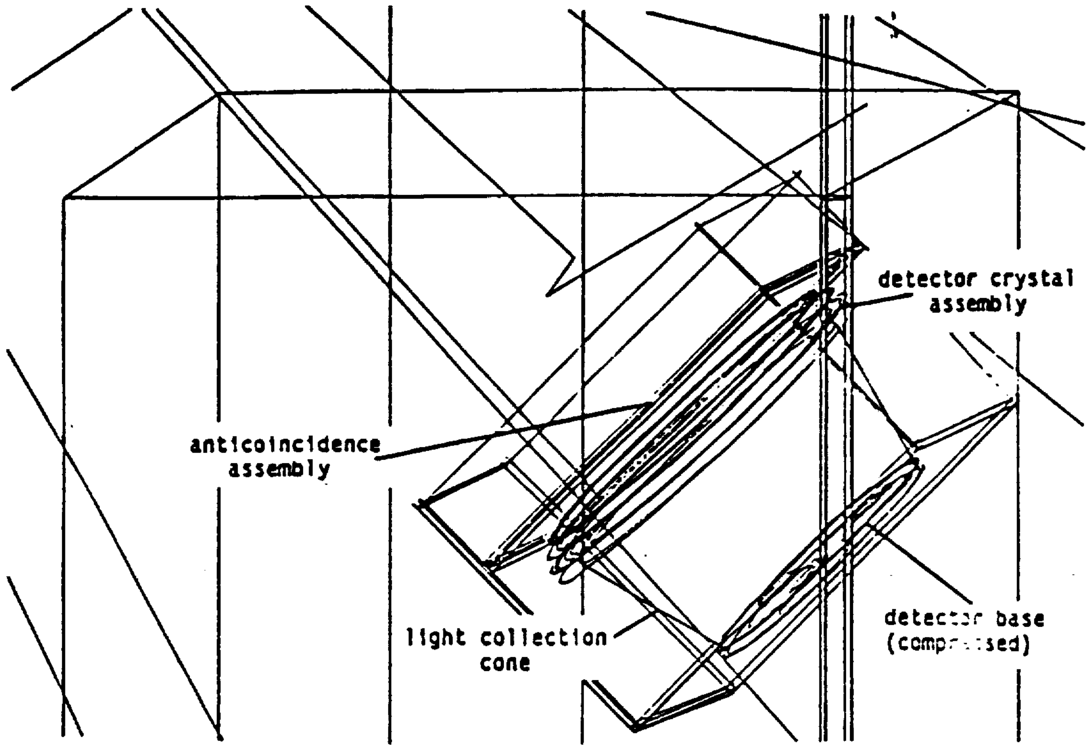

Figure 1. Diagram of simulation geometry used for the Large Area Detector. The detector appears inside a rectangular volume with the outlines of objects in the Absolute Efficiency test environment distributed around it.

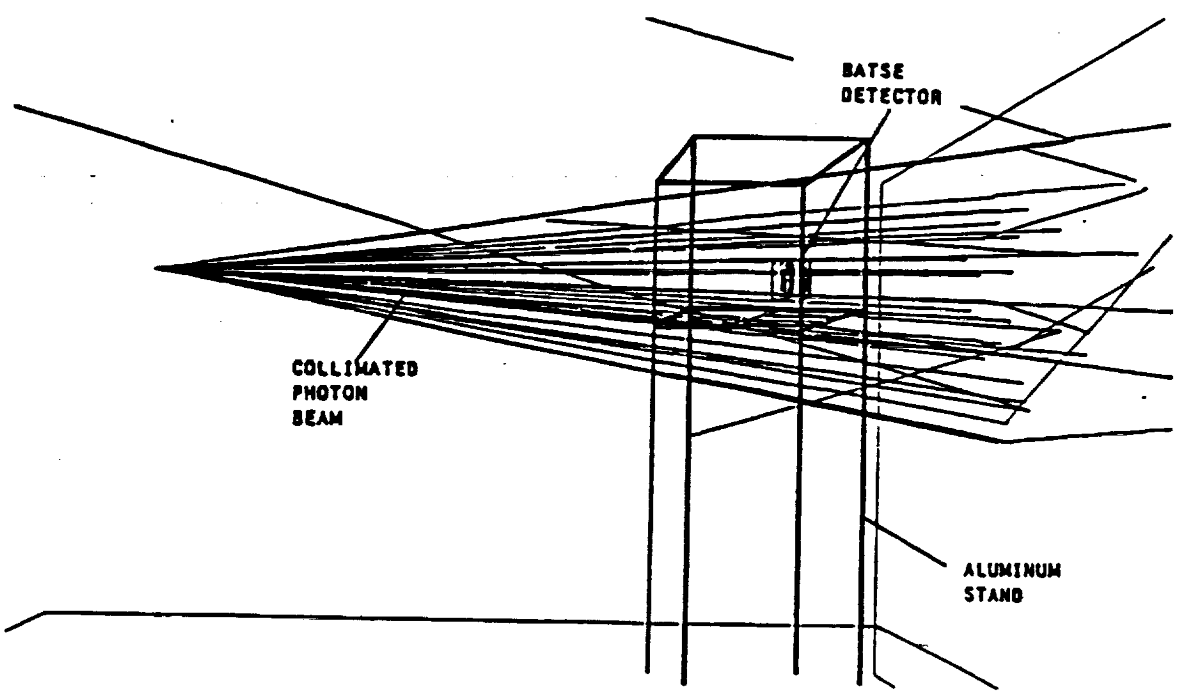

Figure 2. Diagram of simulation geometry used in the Angular Response tests. The detector rests on a raised platform and is exposed to a collimated photon beam.

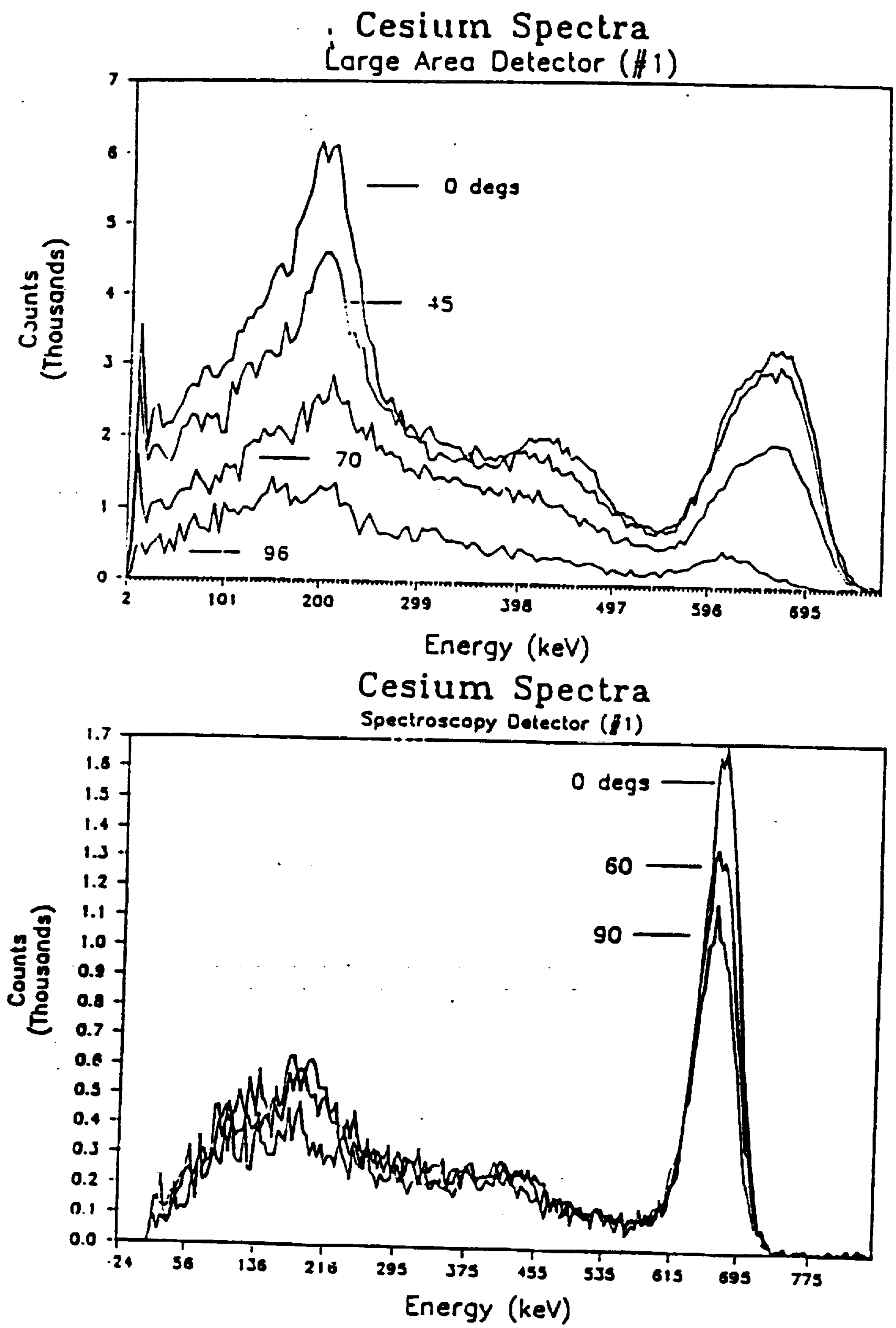

Figure 3. Measured detector response spectra obtained at various angles for the LAD and spec detectors from exposure to a Cs 137 source in the Angular Response tests.

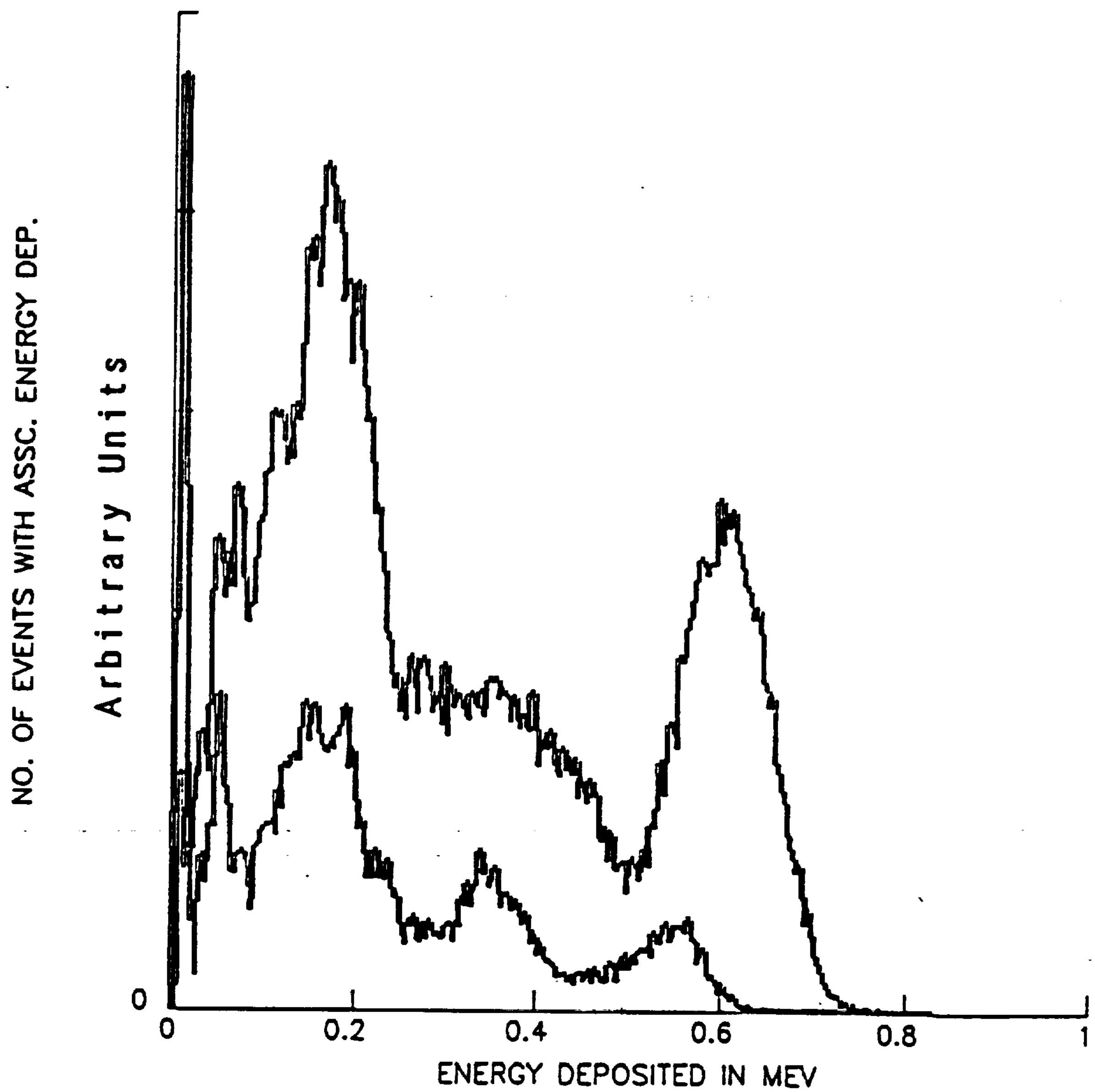

Figure 4. Monte Carlo generated spectra for LAD exposure to Cs 137 source in Angular Response geometry. Spectra at 0 and 90 degree angle of photon incidence are shown. Axes are not normalized to experimental spectra.

Appendix C

(Published in Advances in Space Research)

BALLOON-BORNE HARD X-RAY OBSERVATIONS OF SN 1987A

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ABSTRACT

The region of the Large Magellanic Cloud containing SN 1987A was observed during a balloon-flight of a hard x-ray telescope on 8-10 April 1988. Significant continuum emission was detected in the 45-400 keV range which we attribute to SN 1987A. Compared to an observation with the same instrument in October 1987, the source intensity decreased by ~50% while the spectral shape remained qualitatively the same. This may represent the first clear indication that the hard x-ray emission is entering the declining phase expected as the ejecta become optically thin to the ^{56}Co gamma-rays.

INTRODUCTION

The relative proximity of SN 1987A has enabled astronomers to advance significantly our understanding of supernovae. In particular, the important role of the decay of radioactive ^{56}Co in powering the declining phase of a supernova light curve is now firmly established and gamma-ray lines from ^{56}Co decay have been detected /1,2/.

Continuum x-ray and gamma-ray emission, presumably due to scattered ^{56}Co gamma rays, was detected as early as SN day 180 /3,4/, but the temporal evolution of this emission has been inconsistent with most early theoretical expectations. More recent calculations that involve substantial mixing of ^{56}Co in the expanding gas cloud /5-8/ have had some success in explaining the x-ray and gamma-ray continuum emission. The predicted light curve of the continuum emission is sensitive to the nature of this mixing as well as the density distribution of other elements within the ejecta. Observations of the temporal evolution of the hard x-ray continuum emission can thus provide important model constraints.

EXPERIMENT DESCRIPTION

The balloon-borne payload included two types of detectors: an actively-shielded array of cooled germanium detectors designed to perform high-resolution measurements of gamma-ray line emission, and two large-area, passively-shielded scintillation detectors designed to perform sensitive observations of the hard X-ray continuum and to search for possible emission from a remnant pulsar in the supernova. The results reported herein were obtained with the scintillation detectors, which are adaptations of the large-area detector designed for the Burst and Transient Source Experiment /9,10/ on the Gamma Ray Observatory and were first flown on the present gondola in 1987 October. Details of the instruments as well as the results of that flight have been presented elsewhere /2,11/. The scintillation detectors used in the 1988 April flight differ in one significant respect from the description in /11/: the configuration of the passive slat collimators was changed, resulting in a field of view of 21° FWHM in the elevation direction and 14.2° FWHM in the azimuthal direction. An elevation drive mechanism was added in order to maintain the source region within the detector field of view.

OBSERVATIONS

The payload was launched from Alice Springs, Australia, on 8 April 1988, reaching a float altitude of ~3 mb at 0100 UT on 9 April. The flight was terminated at 0800 UT on 10 April after 31 hours at float. Observations of the region of the LMC containing SN 1987A were performed on 9 April during a period of ~10 hours. The source was also observed during a period of ~7 hours on 10 April. The data from the latter period are of poorer quality due to problems with ground system tape recorders, and so the results presented here are derived entirely from the observing period on 9 April (411 days after the explosion).

Observations were conducted by alternating pointing on-source and off-source in 15-min intervals. The off-source background was obtained by offsetting the field of view by 35° in azimuth from the source in alternating directions (consistent with the avoidance of known, hard x-ray sources) in order to minimize residual systematic effects due to the variation of background vs. azimuth. This program was interrupted between 0830 and 0900 UT in order to conduct observations of the Crab Nebula primarily to confirm pointing accuracy. Observations at other times of the Sun and Venus with onboard sensors also used, confirming pointing to better than 0.5°. The pressure altitude during this period varied between a maximum of 3.3 mb and a minimum of 2.8 mb.

DATA ANALYSIS

The data used for the present analysis consisted of separate 128-channel spectra read out from each detector every 5.5 s. The spectra were corrected for gain drifts by measuring the position of the 511 keV atmospheric background line on 300 s intervals and rebinning the spectra into 16 energy bands, based on a smooth fit to the variation of line centroid with time. The gain variation during the 9 April observing period was 14%.

Figure 1 shows a representative gain-corrected rate history for the 9 April observation. The data have been binned in energy (45-100 keV) and time (~15-min intervals corresponding to on-source and off-source pointing). It is readily apparent from Figure 1 that there is a significant excess flux during the source intervals. We derived the source spectrum in several steps. Firstly, the net count rate due to the source was calculated for each energy band by dividing the off-source intervals in half and subtracting the weighted mean of adjacent off-source rate measurements from each source interval rate. The net rate for each interval was then converted to photon flux at the top of the atmosphere using atmospheric scattering and detector response functions which were calculated analytically. This differs from the analysis used for the previous flight /11/ because calculation of the atmospheric scattering contribution in the latter case was complicated by the much larger detector field of view. The total spectrum was then obtained as the weighted mean of the photon flux values for the individual intervals.

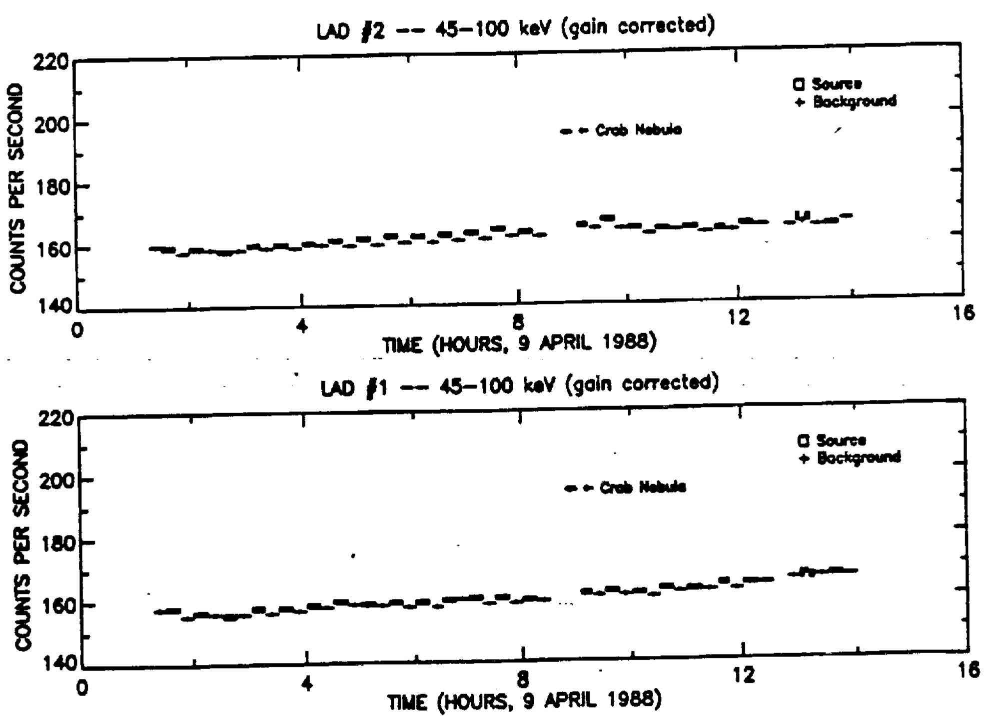
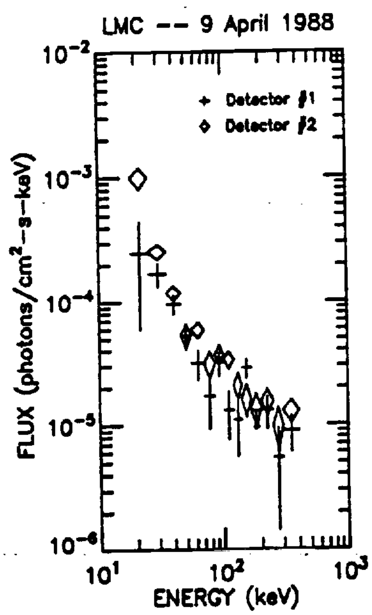


Fig. 1. Gain-corrected counting rate history in the 45-100 keV energy range during the SN 1987A transit on 9 April. The vertical extent of each data point represents its $\pm 1\sigma$ statistical error. The SN pointing program was interrupted between 0830 and 0900 in order to conduct a brief observation of the Crab Nebula.

The photon spectrum as measured separately for each detector is shown in Figure 2. A significant excess flux is apparent in all energy bands up to ~400 keV. Although the data in Figure 2 extend down to 18 keV, we consider only data above 45 keV to be attributable to SN 1987A. As discussed in our previous paper /11/, there are two reasons for this: 1) the spectral analysis performed thus far does not use a full matrix deconvolution, so that the errors in the deconvolved flux are likely to be underestimated at low energies where off-diagonal matrix elements are expected to dominate the response; 2) contributions from other sources cannot be ruled out, even with the smaller field of view used for this flight. Neither of these effects is likely to be important above 45 keV, and so we attribute the detected flux above 45 keV to SN 1987A. Since the full detector response matrix has not yet been constructed, we have not performed detailed model fitting to the data. Nevertheless, it can be seen from Figure 2 that the spectrum is quite hard, with a power-law spectral index $\alpha = 1.3$ above 45 keV. This spectrum is among the hardest yet observed from any source in this energy range.

Figure 3 shows the spectrum after averaging the results from the two separate detectors. For comparison we also show the corresponding data from our 1987 October flight /11/. Even without a full matrix spectral deconvolution, it is clear from Figure 3 that the total source intensity has decreased between the two observations by approximately a factor of two. On the other hand, without more detailed analysis there is no evidence for any difference in spectral shape. Work on spectral deconvolution is in progress and we will present quantitative results in a future publication.



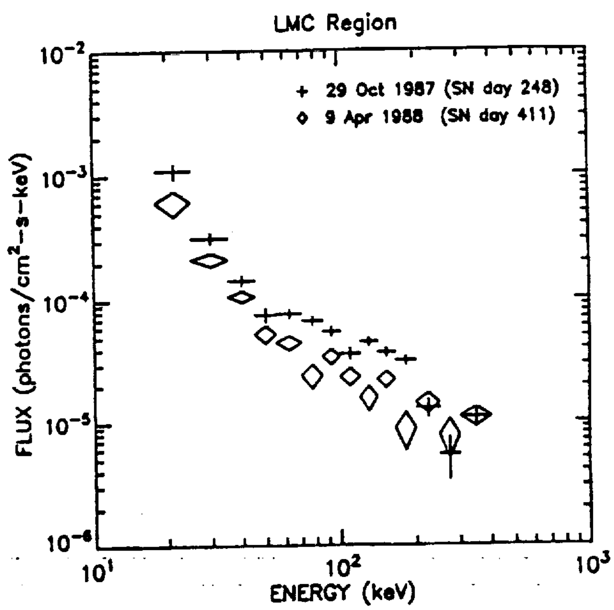


Fig. 2. (left) Spectrum of the LMC region on 9 April as measured separately by the two detectors.

Fig. 3. (right) Spectra of the LMC region at two different epochs. The data for SN day 248 are adapted from /11/. The flux above 45 keV is attributed to SN 1987A (see text).

CONCLUSIONS

By themselves, our measurements indicate a decline in the hard x-ray intensity of SN 1987A by approximately a factor of two between SN days 248 and 410 with no substantial change in spectral shape. Mixed models /5-8/, which are currently favored on the basis of the early appearance of x-ray continuum and gamma-ray line emission /3,4/, generally predict very little change in spectral shape above 45 keV in the interval between our measurements.

In assessing the model predictions of the continuum light curves, it is important to place our measurements in context. Figure 4 summarizes the intensity in the 50-100 keV band as measured by various instruments /3,11-14/. Such comparisons are inevitably difficult because of systematic differences among the instruments, or even between two flights of the same instrument (such as our own, in which the different collimator configurations result in different atmospheric response corrections). Furthermore, the conversion of all the data to the same energy bins involves some assumptions about the true spectrum. Nevertheless, the data present a remarkably consistent picture in which the hard x-ray continuum intensity reached a peak sometime near 0.8 years and is now in the declining phase of its radioactively-powered evolution.

Figure 4 includes for comparison a theoretical light curve /6/ which appears to reach its peak later than the data would suggest. Further observations of the SN 1987A x-ray and gamma-ray continuum are obviously warranted, not only to trace the decline in the radioactivity but also to search for a possible remnant pulsar. We are scheduled to fly the same instrument again from Australia in the fall of 1988. Since our instrumental sensitivity limit is approximately a factor of 5 below the 1988 April observations, we expect to be able to provide further useful constraints on models of SN 1987A.

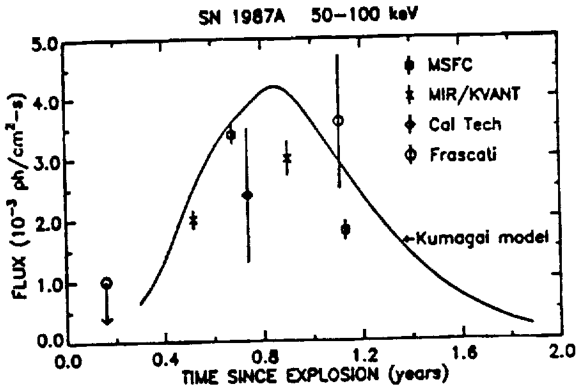


Fig. 4. The light curve of SN 1987A in the 50–100 keV energy range. MIR/KVANT points are adapted from /3/and /12/. CAL TECH (GRIP) points are adapted from /13/. The Frascati points are adapted from /14/. The solid curve was calculated for a model in which ^{56}Co and other heavy elements are mixed into the outer hydrogen-rich ejecta /6/.

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Appendix D

(Published in Bulletin of the American Astronomical Society)

Attachment

Bulletin of the American Astronomical Society, p. 960:

5.08

Analysis of Hard X-Ray Observations of SN 1987A

G.N.Pendleton, W.S.Paciesas (UAH), G.J.Fishman, R.B.Wilson, C.A.Meegan (NASA/MSFC)

Continuum hard X-ray and gamma-ray spectra from SN 1987A in the energy range from 25 keV to 400 keV are presented. The analysis of data taken on 29-31 October 1987 and on 8-10 April 1988 with modified balloon-borne BATSE detectors is described. The generation of the detector response matrix produced using a combination of laboratory measurements and EGS Monte Carlo simulations is discussed. A Monte Carlo technique for transporting a gamma-ray flux from the top of the atmosphere to balloon altitudes is presented.

Bulletin of the American Astronomical Society, p. 1069

52.02

Hard X-Ray Observations of SN1987A

G.J. Fishman, R.B. Wilson, C.A. Meegan (NASA/MSFC), W.S. Paciesas, G.N. Pendleton (UAH)

Balloon-borne observations of SN1987A have been performed from Alice Springs, Australia in the energy range 45-400 keV. NaI scintillation detectors, 1.27 cm thick with a total area of 4050 cm^2 were flown with passive shielding and collimators. These detectors were derived from those designed for the Burst and Transient Source Experiment for the Gamma Ray Observatory. Two balloon flights have been performed with these detectors, on October 29-31, 1987, and April 8-10, 1988, (SN days 248 and 411). The observed spectrum was similar and quite hard on both dates, having a photon power-law spectral index near -1.3. However, the intensity decreased by nearly 50% during this interval. The spectral shape and time evolution are in good agreement with the models of SN1987A which attribute the hard X-ray emission to highly Comptonized radiation from higher energies. Another balloon flight is planned for Oct/Nov 1988.

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